# SOLAR IRRADIANCE OBSERVED FROM PVO
# AND INFERRED SOLAR ROTATION

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## ABSTRACT
Solar irradiance in the EUV has been monitored for 11 years by the Pioneer Venus Orbiter (PVO). Since the experiment moves around the Sun with the orbital rate of Venus rather than that of Earth, the measurement gives us a second viewing location from which to begin unravelling which irradiance variations are intrinsic to the Sun, and which are merely rotational modulations whose periods depend on the motion of the observer.

We confirm an earlier detection, made with only 8.6 years of data, that EUV irradiance is modulated by rotation rates of two families of global oscillation modes. One family is assumed to be r-modes occupying the convective envelope and sharing its rotation, while the other family (g-modes) lies in the radiative interior which has a slower rotation. Measured power in r-modes of low angular harmonic number ($\ell \leq 7$) indicates that the Sun's envelope rotated about 0.7% faster near the last solar maximum (1979 thru 1982) than it did during the next rise to maximum (1986 thru 1989). No change was seen in the g-mode family of lines, as would be expected from the much greater rotational inertia of the radiative interior.

## THE EUV DATA
The Langmuir probe on the Pioneer Venus Orbiter (PVO) measures a photoemission current which is a proxy for the solar extreme ultraviolet flux (EUV) when PVO is outside the ionosphere of Venus (see Brace et al., 1988). The measured flux covers the wavelength range from about 30 to 130 nm. A measurement of the quantum efficiency of the probe surface material, Rhenium, performed at the National Institute of Standards and Technology, showed that the contributions to the measured photoelectron current are:

| | | |
|---|---|---|
| 56% (from H Ly$\alpha$, 121.6 nm), | 28% from the continuum between 30 and 110 nm, | |
| 4% (from He II at 30.4 nm), | 2% (He I, 58.4 nm), | 2% (O V, 62.9 nm), |
| 4% (C III, 97.7 nm), | 2% (H Lb, 102.6 nm), and | 2% (O VI, 103.2 nm). |

For details of the instrument see Krehbiel et al. (1980). Nearly 11 years of daily values of the flux were available, from day 343 of 1978 to day 328 of 1989, except for times of superior conjunction when data transmission from Venus was not possible. Brace et al. (1988) have given translations of the Langmuir probe current ($I_{pe}$, unit $10^{-9}$ amps) into EUV flux in photon cm$^{-2}$ s$^{-1}$ and also into the often used 10.7 cm flux value. They also discussed the utility of the Venus-based solar measurements for studies of how solar variability affects the ionosphere, atmosphere, and magnetosphere of Venus. A shorter segment of the EUV

flux data was used in two earlier studies of solar periodicities: Hoegy and Wolff (1989), Wolff and Hoegy (1989, herein: "Paper I").

The upper panel of Figure 1 shows the 11 year record of solar EUV flux. To de-emphasize the larger fluctuations at solar maximum, we divided the data by its 400 day running mean to produce the more uniform sequence plotted below it. The lower panel is the data set that will be Fourier-analyzed.

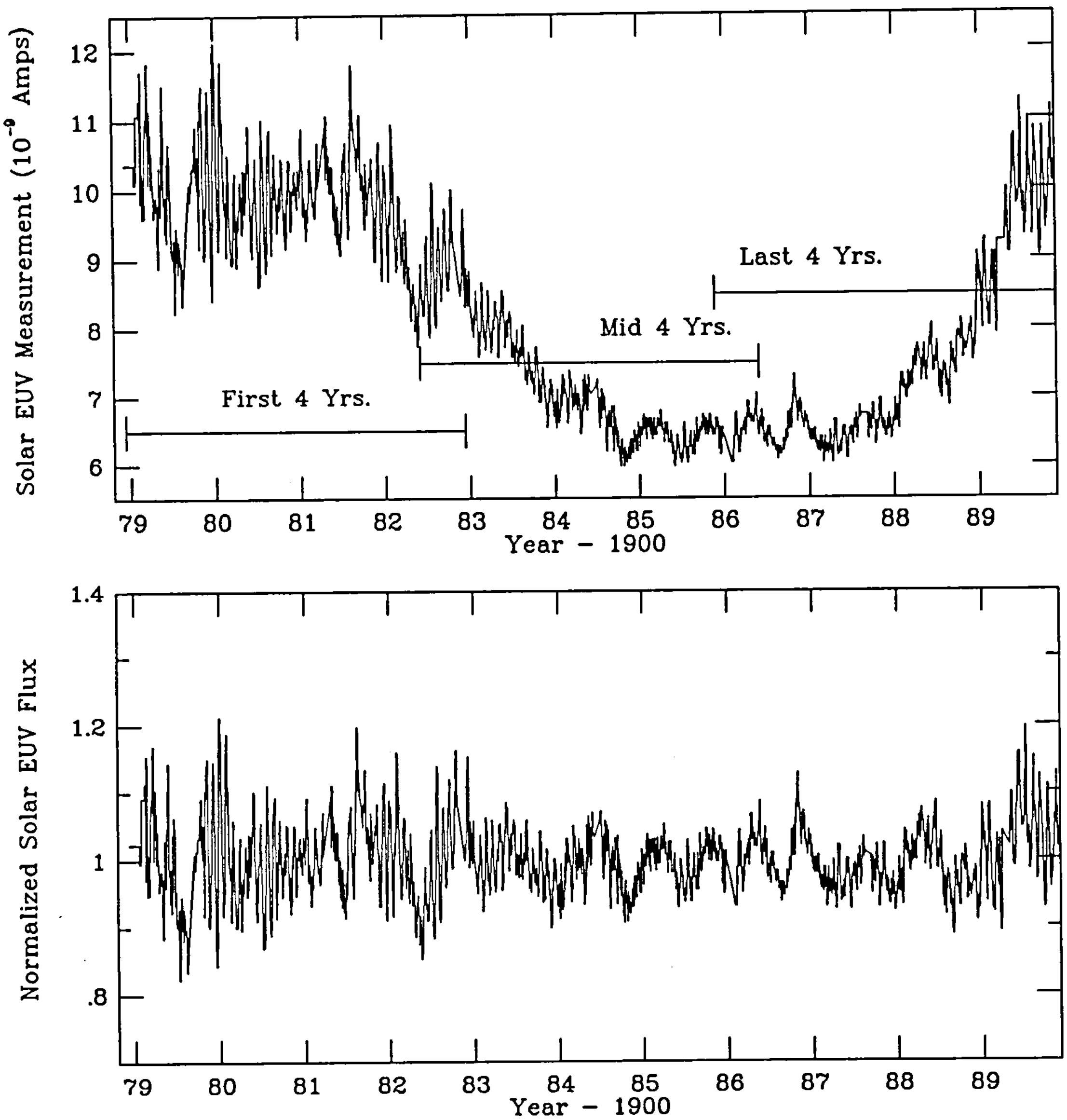



Figure 1--The upper panel shows the probe current which is proportional to solar EUV flux. It declines by about 35% after the maximum of the 11 year solar cycle. Dividing this data by its 400-day running mean produces the data set in the lower panel.

## FOURIER SPECTRUM

Figure 2 shows a Fourier spectrum of the 11 year EUV data set. We plot amplitude (the square root of the power). The upper scales emphasize that a peak on this graph representing a solar rotation period will be seen at one period in the Venus experiment and at a shorter period if viewed from Earth, due to the orbital motions. However a peak caused by an intrinsic solar fluctuation happening at all longitudes, will be seen at the same period and frequency from any planet.

Four features stand out in the observed spectrum.

1. The broad cluster of peaks between 350 and 460 nHz is caused, in part, by solar surface rotation rates. The two tallest peaks may be due to prominent, long-lasting features fixed to the solar surface. If so, they would be seen from Earth as 27.0 and 28.0 day periods.
2. Amplitudes near those two tall peaks appear to have a weak first harmonic; see cluster between 780 and 830 nHz.
3. There is a steady rise in amplitude as frequencies decrease below 130 nHz. This is caused by the dense collection of g-mode beat frequencies identified in the sunspot record by Wolff (1983). The measured amplitudes would increase all the way to the origin except that our analysis suppressed the lowest frequencies when dividing by the 400-day running mean.
4. As in Paper I, we attribute the very strong peaks near 105 nHz and 105/2 to the lowest harmonic r-mode ($\ell = 1$). This determines the mean sidereal rotation rate of that mode,
$$\nu_{r1} = -1.0 \pm 1.5 \text{ nHz}, \tag{1}$$
and thus updates the values, 106 nHz and $-1.5 \pm 1.5$ nHz , found in Paper I using a shorter time interval. A characteristic of the observed spectrum is the aliasing of many lines by $\pm 105$ nHz due to the nonlinear interaction between this r-mode and other oscillation modes.

Finally, lines in the spectrum tend to be split by a distracting fine structure; the average spacing between maximums is only 4.1 nHz. A considerably larger average spacing ($\approx$10 nHz) was found in an earlier analysis of most of this data (Paper I). The fine structure is caused by aliasing between strong signals in the two solar maximum periods contained in the present data set, whereas the older analysis terminated in 1987 and contained only one solar maximum. The insert on Figure 2 shows how the fine structure distorts the signature of the $\ell = 1$ r-mode. Without the ripples, the cluster of power between 95 and 115 nHz might be a fairly smooth peak with a maximum at 2F. The measured spectrum near 2F is consistent with an r-mode having two active longitudes per rotation (symmetry, S = 2) and having a larger amplitude near the 11 year solar maximums. We adopt this interpretation. The width of the cluster implies that the amplitudes are strong for roughly three years at a time and significantly weaker during the intervening solar minimum. The presence of power at F too shows that the S=1 component is not at all negligible for this mode.

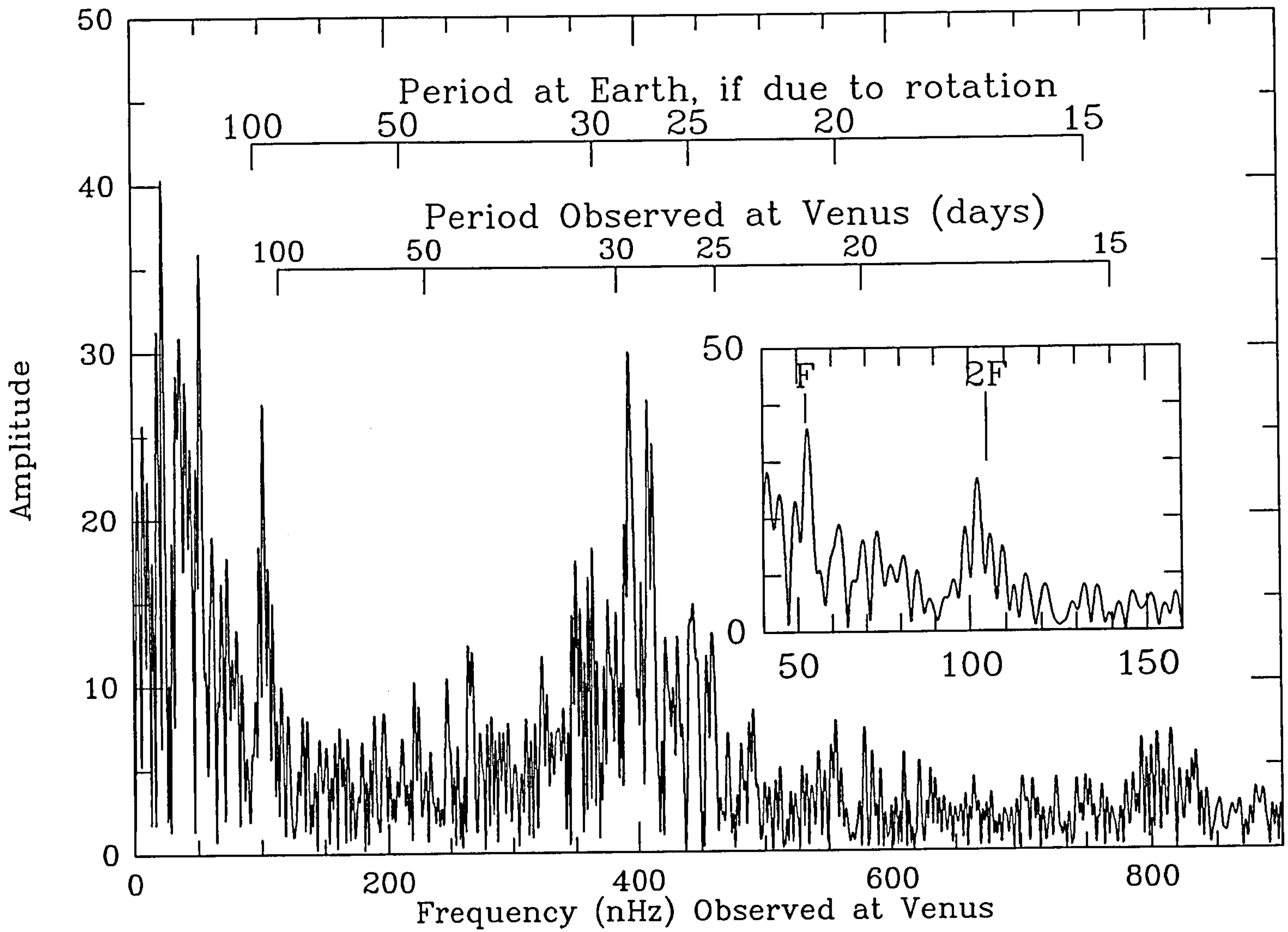



Figure 2 -- Fourier spectrum of the 11 years of normalized EUV flux shown on bottom panel of Figure 1. Below 130 nHz, the spectrum is influenced by g-mode beat frequencies and by the r-mode for $\ell = 1$ which causes very strong lines at F and 2F (see insert).

## THE INTERIOR MODES (g-MODES)

Beat frequencies from the rotation of g-modes in the Sun's radiative interior seem to have influenced the sunspot record of the last two centuries. Wolff (1983) observed the frequencies and determined the sidereal rotation rate of each mode, multiplied by a symmetry factor S whose value was either 1 or 2. Since then, the symmetry S = 2 has fit observations best and has been adopted. For $\ell > 1$, Table 1 lists the sidereal rotations found in 1983 for all nonlinear g-modes which our EUV data is able to resolve. The value for $\ell = 1$ is less certain and was suggested in Paper I based on most of the EUV data.

**TABLE 1**

**Standing Solar g-modes**

| | Sidereal Rotation | | Main EUV Fluctuation Expected | |
|---|---|---|---|---|
| $\ell$ | Frequency (nHz) | Period (days) | Frequency (nHz) | Period (days) |
| 1 | 176. | 65.8 | 354. | 32.7 |
| 2 | 314.7 | 36.8 | 631.3 | 18.33 |
| 3 | 351.9 | 32.9 | 705.8 | 16.40 |
| 4 | 362.0 | 32.0 | 725.9 | 15.94 |
| 5 | 368.3 | 31.4 | 738.6 | 15.67 |
| 6 | 371.9 | 31.1 | 745.9 | 15.52 |
| G | 380.1 | 30.5 | 762.2 | 15.19 |

As pointed out in Paper I, we do not expect to see g-mode rotation rates easily at the surface because their amplitude declines exponentially in the convective envelope. Rather, we expect to see the results of eruptions stimulated when their active longitudes near the base of the convection zone rotate past those of prominent global modes in the envelope. Since the $\ell = 1$ mode in the envelope should be the most important for our experiment (which integrates over the full solar disk), the most detectible frequencies in the rotational range should be,

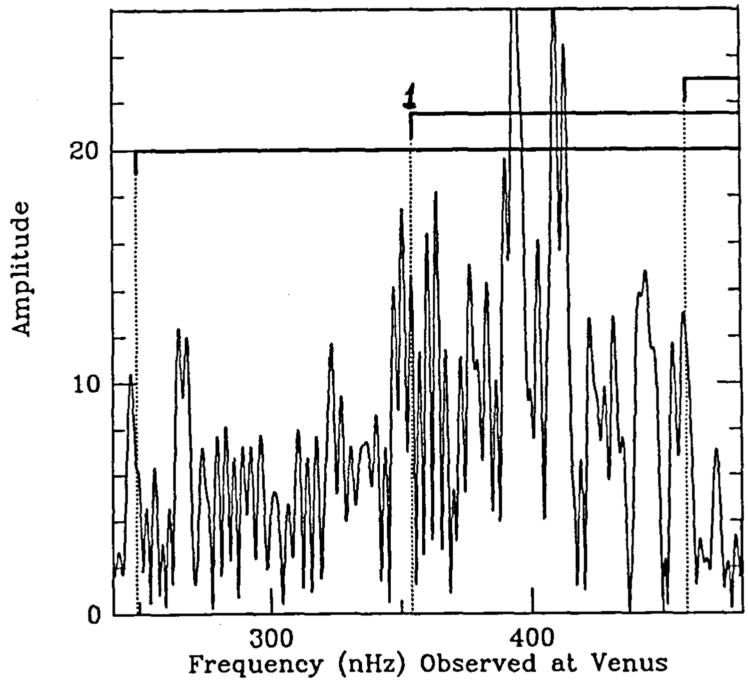
$$\nu_b = 2(\nu_g - \nu_{r1}) , \tag{2}$$

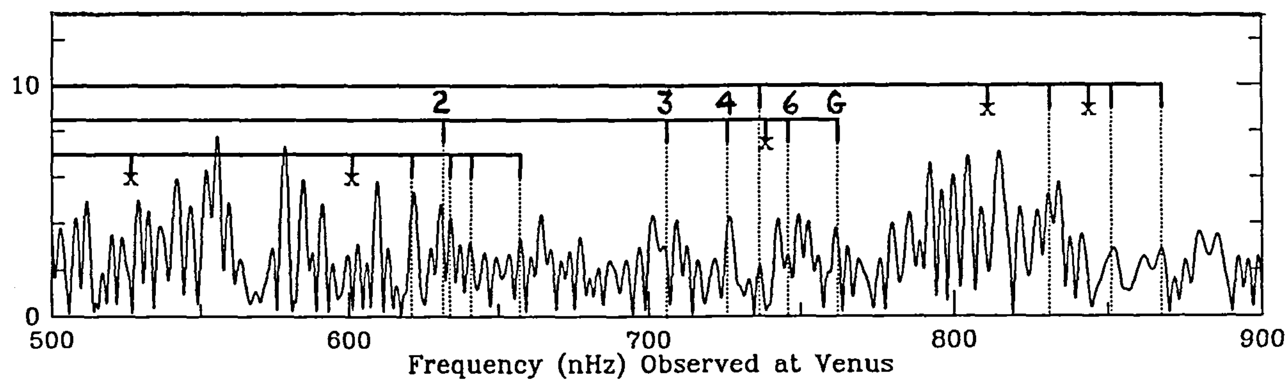
where $\nu_g$ is the g-mode rotation rate (second column of Table 1), and the factor 2 is the symmetry. Imposing equation (1), fixes the frequencies $\nu_b$. The right side of Table 1 lists them and corresponding periods, $\nu_b^{-1}$. The seven frequencies plus their aliases at ±105 nHz make a set of 21 theoretical lines. We would expect to detect them all if there were not confusion from many other aliases and another family of modes in part of the same range (r-modes, below). Even so, only 5 frequencies (marked X) are not detected in the EUV spectrum, magnified on Figure 3. The detection criterion is that a theoretical line be closer to an obsereved maximum than to a minimum. The binomial expression gives probability of accidental agreement as < 1% which confirms the detection of much higher statistical significance (Wolff, 1983) based on beat frequencies rather than rotation rates.

The three theoretical lines with frequencies <500 nHz are due to the g-mode for $\ell = 1$. They cause strong observed lines which seem to be broader and, therefore, more conspicuously subdivided by the fine structure. Perhaps, their actual effect would be modelled better by smooth peaks, about 10 nHz wide, fitted to the three clusters of observed power in the vicinity of each. Independent confirmation is needed that these are indeed due to the $\ell = 1$ g-mode.

The periods in the right column of Table 1 should appear with identical values whether detected from Venus or Earth since they are intrinsic periods of the Sun.

Figure 3--The degree of correspondence of g-mode frequencies (Table 1) with magnified portions of the EUV spectrum (Figure 2). Of the 21 lines, only 5 (marked X) are not detected. The g-mode spectrum appears 3 times due to aliasing at ±105 nHz caused by interaction with the lowest harmonic r-mode.




**THE ENVELOPE MODES (r-MODES)**

Many observers have reported changes in the rate of solar surface rotation at a given latitude. To see if the entire convective envelope might vary its mean rotation with time, we analyzed data from three, partly overlapping four year periods. Figure 4 shows the Fourier spectrum of each. The centroid of the high amplitude cluster near 400 nHz seems to occur at lower frequencies during the last four years (bottom panel). This region is typical of solar surface rotation since a rotation period seen from Venus as $(400\text{ nHz})^{-1}$ would be seen from Earth as 27.6 days. If some of this shift in the centroid is due to a slowing of the mean sidereal rotation, $\nu_\infty$, of the convective envelope, then the sequence of r-mode rotation rates,

$$\nu_\ell = \nu_\infty[1 - 2/\ell(\ell+1)] \qquad (2)$$

is reduced proportionally. The frequencies expected at Venus are twice the synodic rates,

$$\nu_{obs} = 2(\nu_\ell - 51.5\text{ nHz}), \qquad (3)$$

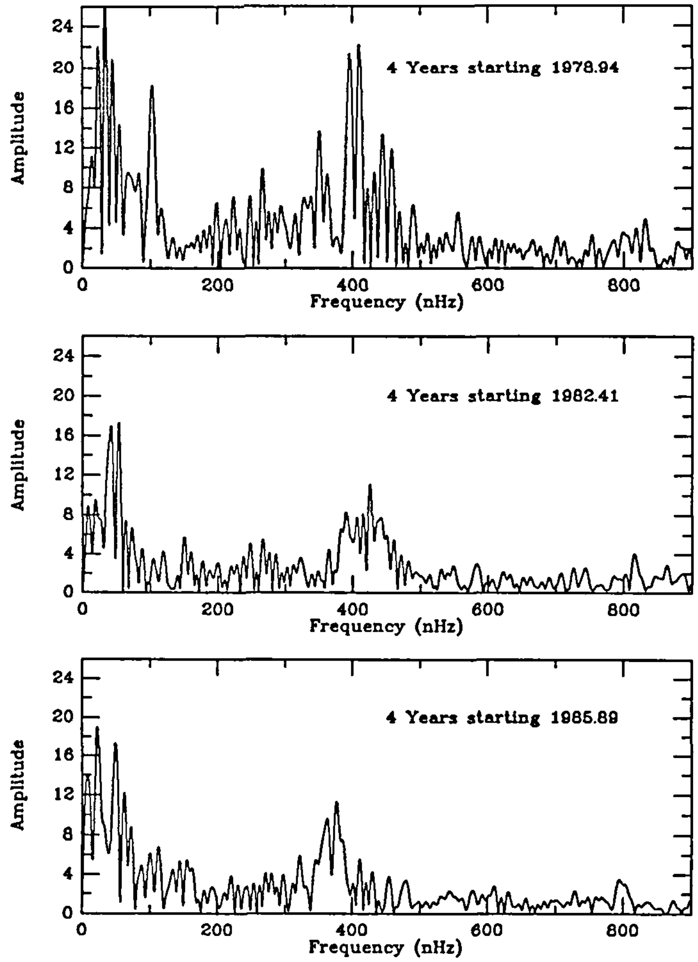



Figure 4--Fourier spectrums of the first, middle, and last 4 years of EUV data. They are quite different because 4 years is not nearly long enough to capture the full complexity of solar behavior. Typical solar surface rotation rates fall within the broad cluster of peaks near 400 nHz. The cluster is shifted to lower frequencies in the last four years, suggesting a slower average rotation during that interval.

and also the aliases, $\nu_{obs} \pm 105$ nHz. The sequence $2 \leq \ell \leq 7$ gives a group of 18 lines to test whether $\nu_\infty$ has changed. (Frequencies for $\ell > 7$ are too close to be resolved by this four year data set and the $\ell = 1$ mode is independent of a change in $\nu_\infty$ to first order.) Of the 18 lines, we detected respectively, 13 or 14 using the values of $\nu_\infty$ shown in Table 2. They are listed as sidereal rates and then converted to synodic values.

**Table 2**
**Mean Rotation of Convective Envelope**

| Observed Interval | Sidereal Rate | Apparent from Earth | |
|---|---|---|---|
| | | Rate | Period |
| | (nHz) | (nHz) | (days) |
| First 4 Years, 1978.9 – 1982.9 | 460.0 ± 2. | 428.3 | 27.02 |
| Last 4 Years, 1985.9 – 1989.9 | 456.7 ± 2. | 425.0 | 27.23 |

For an observer on Earth, the table shows that the mean rotation period of the convective envelope (as averaged by the r-modes) was 27.02 days during the first four years and 27.23 in the last four years. For the last four years, the deviation of each observed line from a predicted line is shown on Figure 5; vertical separations are for clarity. The four lines that failed our detection criterion are the two most extremely left or right. The very high degree of clustering argues for the reality of the fit since randomly chosen frequencies would appear with equal probability anywhere along the horizontal range of 11 nHz which is the mean separation of maximums on Figure 4.

These fits are the best we found and the only ones close to 27 days. But, if it is conceivable that the Sun's convective envelope could change its speed by 4% or more during the 11 year interval, then several other solutions are possible. They are of lesser quality and more likely to be statistical accidents but we can't rule them out from the EUV data alone.

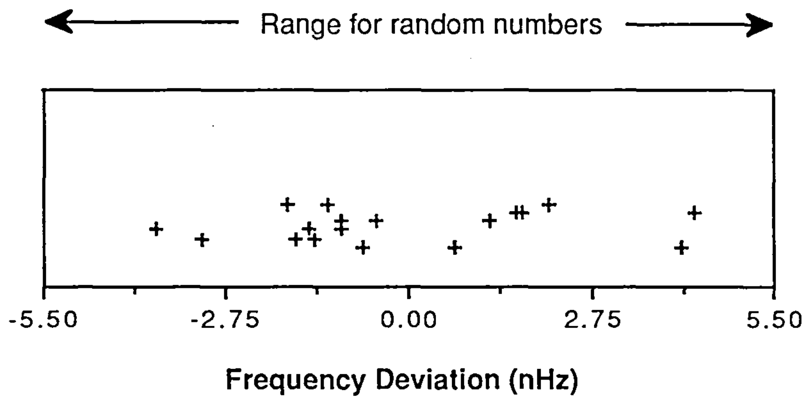



Figure 5--Deviation of peaks in the observed spectrum from the 18 frequencies caused by the rotation of solar r-modes. Concentration toward the central half of the plot confirms the r-mode interpretation since an irrelevant model, or random frequencies, would populate the entire horizontal range.

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